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NuMI BeamLine Design

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Trajectory:

- 3 major bend centers steer protons extracted from the MI-60 straight 374 m through the existing tunnel to the NuMI target.

  -3 Lambertsons & 1 C-magnet at Q608 extract protons vertically. Powering the 2 downstream Lambertsons & C-magnet 20% above their nominal 120 GeV/c fields creates sufficient vertical clearance to insert a rolled 3Q120 quad between the C-magnet & Q109.
  - 6 rolled EPB's level the beam off and steer it onto its final horizontal trajectory.
  - 6 vertically-bending B2's pitch the beam down through the carrier pipe.
  - 4 final B2's align the beam vertically onto the target & towards the Soudan detector.

DIPOLES					
String	Type	#	Length (m)	B (T)	Roll
HV1	EPB	1 2 2 1	3.048	1.4986	1.61^{o} 33.00^{o} 36.51^{o} 33.00^{o}
V2	B2	6	6.0706	1.7148	90^{o}
V3	B2	4	6.0706	1.6103	90^{o}

Table 1. Magnet parameters of the 3 major bend centers.
[Design fields : EPB = 1.5 T @ 1.688 kA : B2 = 1.8 T @ 4.750 kA]

BEAMLINE OPTICS:

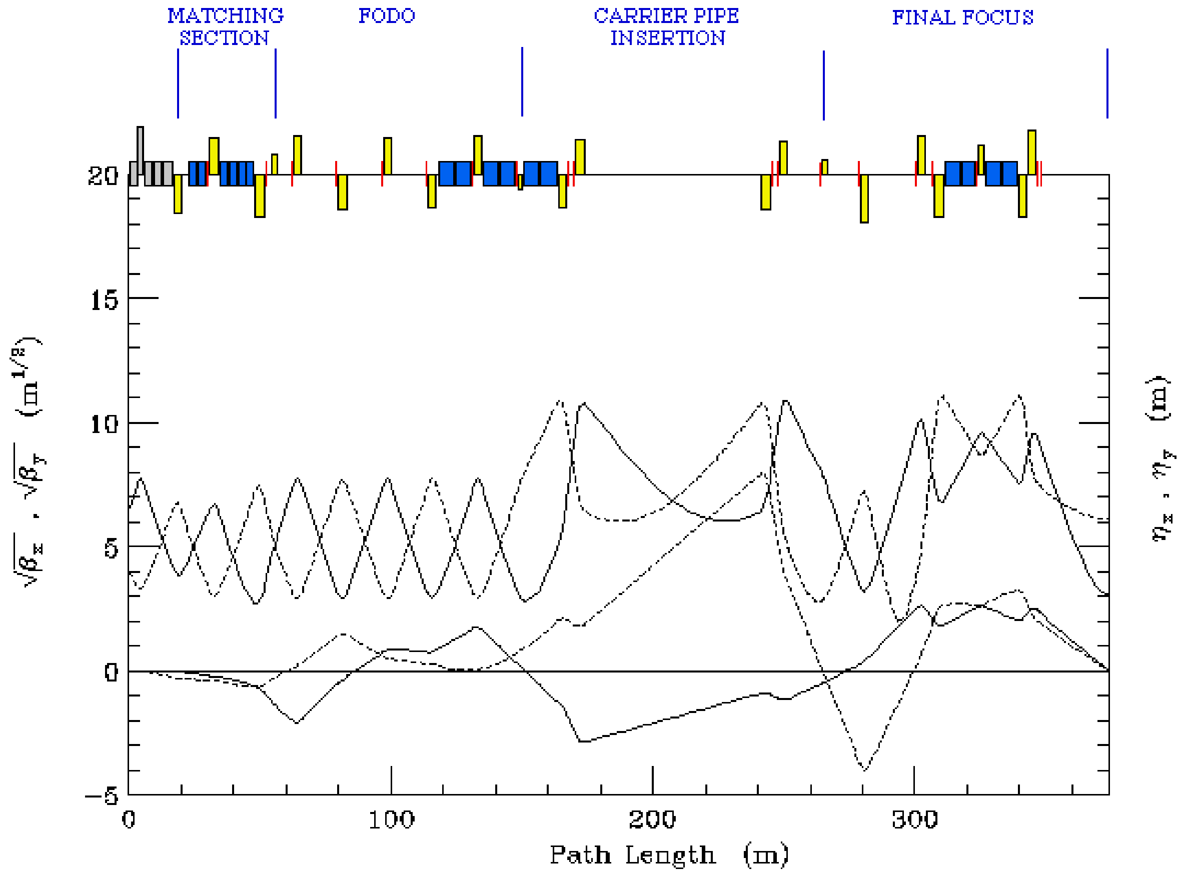

Figure 1. Lattice functions of the NuMI line [vertical = dashed ; horizontal = solid].

- 21 quadrupoles of the 3Q60/120 series define the optics. Each quad has a BPM and, with the exceptions of Q101 & Q104, also a dipole corrector.
- The beamline is comprised of 4 major optical modules:

  - 4 quads match β's & α's from the MI into the transport line;
  - a section of repetitive FODO cells which essentially replicate the MI lattice functions;
  - a straight section insert similar to those of the Tevatron for crossing the forbidden carrier pipe. Peak $\beta_x = \beta_y = 120$ m;
  - a final focusing module to create the desired beam size at the target and fix dispersion $\eta_x = \eta_y = 0$. [The single horizontal bend center, plus the vertical tunnel constraints preclude also achieving $\eta_x' = \eta_y' = 0$]. $\beta_x(\max) \approx 100$ m, and $\beta_y(\max) \approx 120$ m.

QUADRUPOLES		
Quad #	Length (m)	Gradient (T/m)
Q101	3.048	13.2876
Q102	3.048	12.3403
Q103	3.048	14.6796
Q104	1.524	6.9234
Q105 / 106 / 107 / 108 / 109	3.048	12.3445
Q110 / 115	1.524	5.0768
Q111 / 114	3.048	11.5134
Q112 / 113	3.048	12.1383
Q116	3.048	16.2339
Q117	3.048	12.9807
Q118	3.048	14.5280
Q119	1.524	9.9047
Q120	3.048	14.8634
Q121	3.048	14.8351

Table 2. Quadrupole circuits and parameters.
[Design fields = 18.9 T/m @ 100 A]

- Q101 $\rightarrow$ Q104 are powered individually for MI $\rightarrow$ NuMI matching.
- Q105 $\rightarrow$ Q109 in the FODO section run in series.
- Corresponding pairs Q110/Q115, Q111/Q114, & Q112/Q113, upstream & downstream of the straight section are powered together.
- Q116 $\rightarrow$ Q121 are powered individually to match from NuMI to the desired spot size & beam parameters on the target.
- All gradients are comfortably below the magnet design values.

FINAL FOCUS OPTICS:

- The optics shown in Fig.1 has β_x = 9.40 m, β_y = 37.60 m, $\alpha_x = \alpha_y = 0$ at the target, which, for a 40π (95%, normalized) beam gives a spot size of σ_x = 0.70 mm, and σ_y = 1.40 mm.

- The final focus must be sufficiently flexible to maintain the desired spot size over a wide range of emittances, reflecting current MI operations & possible future evolution. Tuning curves for the last 4 magnets are shown in Fig.2. β_{max} never exceeds ~135 m (~6% increase in beam size).

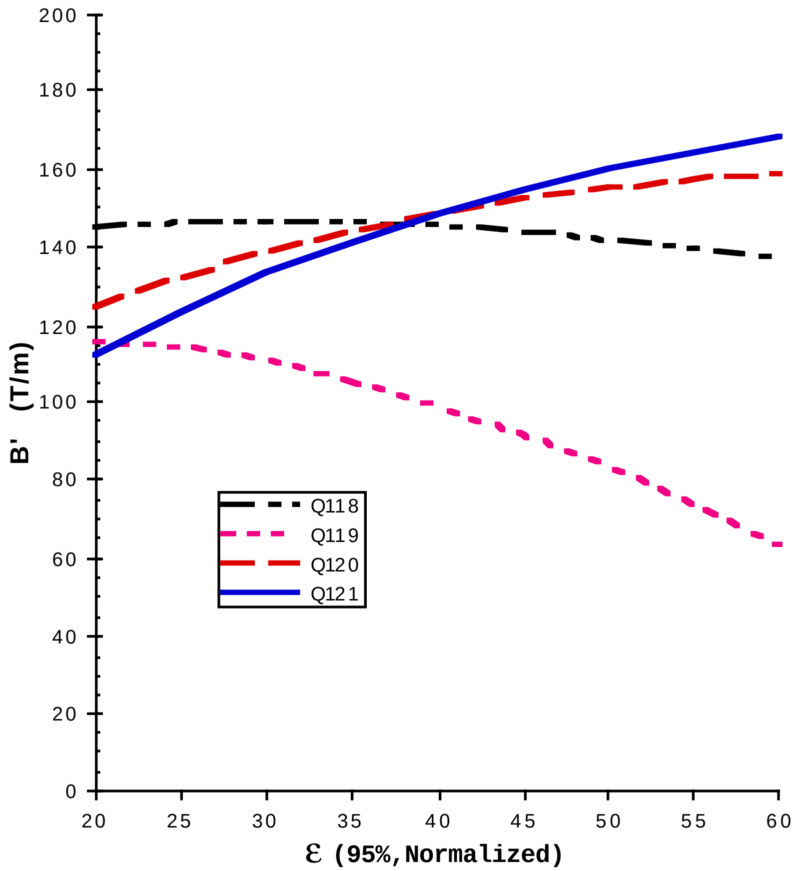

Figure 2. The Q118 → Q121 gradients that produce σ_x = 0.70 mm, σ_y = 1.40 mm, and $\alpha_x = \alpha_y = 0$, at the target as beam emittance varies.

- All 6 FF quadrupoles are needed to also maintain $\eta_x = \eta_y = 0$ at the target, but this refinement is probably not necessary. For $\delta p_{95}/p$ = 7.E-4, and emittances in the range 20 → 60π, dispersive contributions to spot size never exceed 2 μm in σ_x and 25 μm in σ_y.

ODE TO B2'S

- Using B2 magnets to comprise the last bend center has huge optical advantages. The ability to design a final focus section with a large tuning range is a direct consequence of this.

- Use of 4 B2's, rather than a 9 magnet mix of 5-1.5-120 & 6-3-120 dipoles liberates >18' of tunnel space, which is significant. Some consequences are:

  - the lever arm between the final 2 sets of targeting BPM's is increased by ~2 m;

  - a doublet can be used as the last 2 FF magnets to establish low-β optics ($\alpha_x = \alpha_y = 0$) at the target. It is then possible to keep β_{max} ~120 m. A doublet is not possible with a 9 dipole mix & β_{max} in one plane will always reach ~300 m — the aperture gain of a 6-3-120 is then squandered by the larger beam size.

- within the pre-target tunnel there is enough room for 4 quad+BPM+corrector packages, compared with just 3 for the dipole mix.

- With B2 magnets then design of the FF section is driven by the desired optical properties, rather than the available space.

GRADIENT ERRORS:

- Sensitivity of the optics to random gradient errors has been simulated. With errors of σ(ΔB'/B') = 25E-4 assigned to the 21 quadrupoles for 10 random seeds, Δβ/β never exceeds ≈6%, or, an ≈3% increase in beam size.
- The change in beam σ's are < 60 μm, and at the target the maximum changes in beam size are on the order of 20–30 μm.

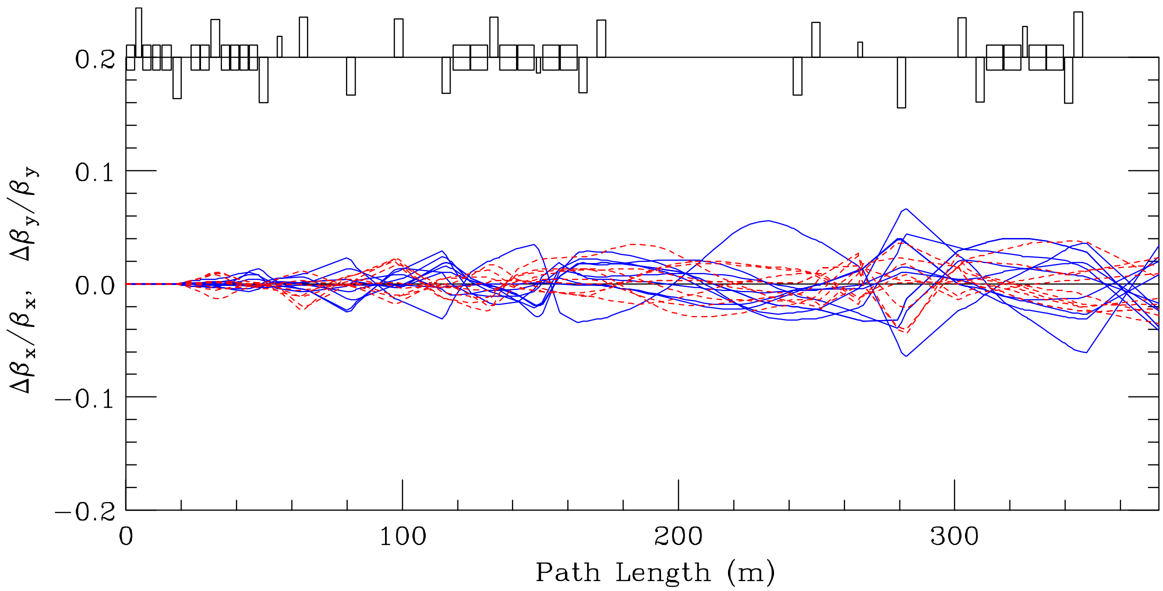

Figure 3. β–waves due to random gradient errors with σ(ΔB'/B') = 25E-4.

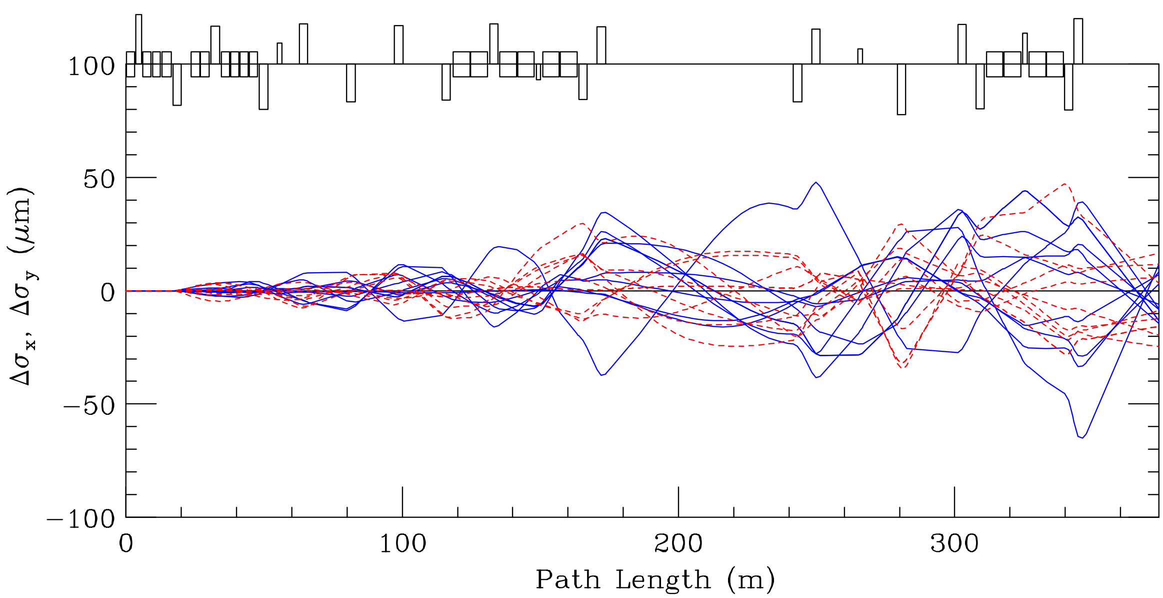

Figure 4. Beam size variation resulting from random gradient errors.

INJECTION OPTICS ERRORS:

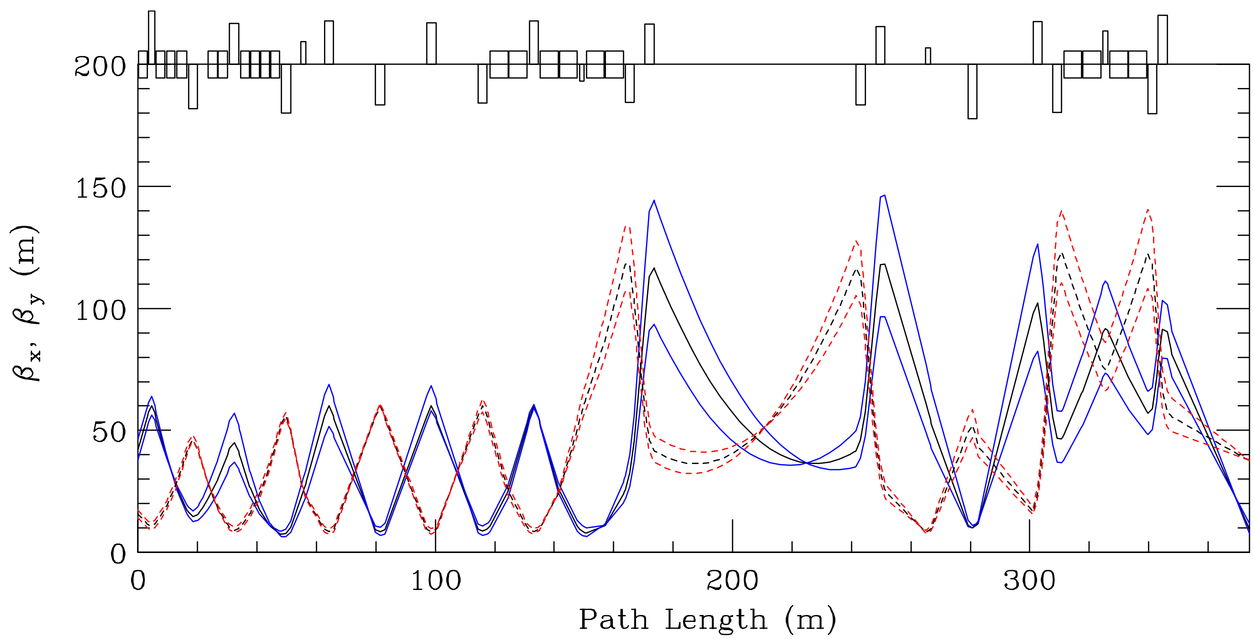

Figure 5. β-waves due to ±10% MI injection β errors.

- Shown are the β-envelopes resulting from ±10% variations in the nominal MI β_x & β_y injection values.
- The MI-end matching section can be retuned to eliminate the mis-match, but this isn't strictly necessary — the maximum β's are sufficiently well-behaved that there isn't an aperture problem. The residual mis-match at the target can be corrected by the final focus quadrupoles.

TRAJECTORY CORRECTION:

- Central trajectory errors are simulated with random magnet mis-alignments & dipole field errors:

$$\sigma(\Delta x, \Delta y) = 0.25 \text{ mm}, \ \sigma(\psi_{roll}) = 0.50 \text{ mr}, \ \& \ \sigma(\Delta B/B) = 25\text{E-}4.$$

- Uncorrected offsets from 10 random generator seeds:

$\Delta x(rms) = 1.24$ mm $\Delta y(rms) = 1.47$ mm

$\Delta x(max) = 6.94$ mm $\Delta y(max) = 6.27$ mm

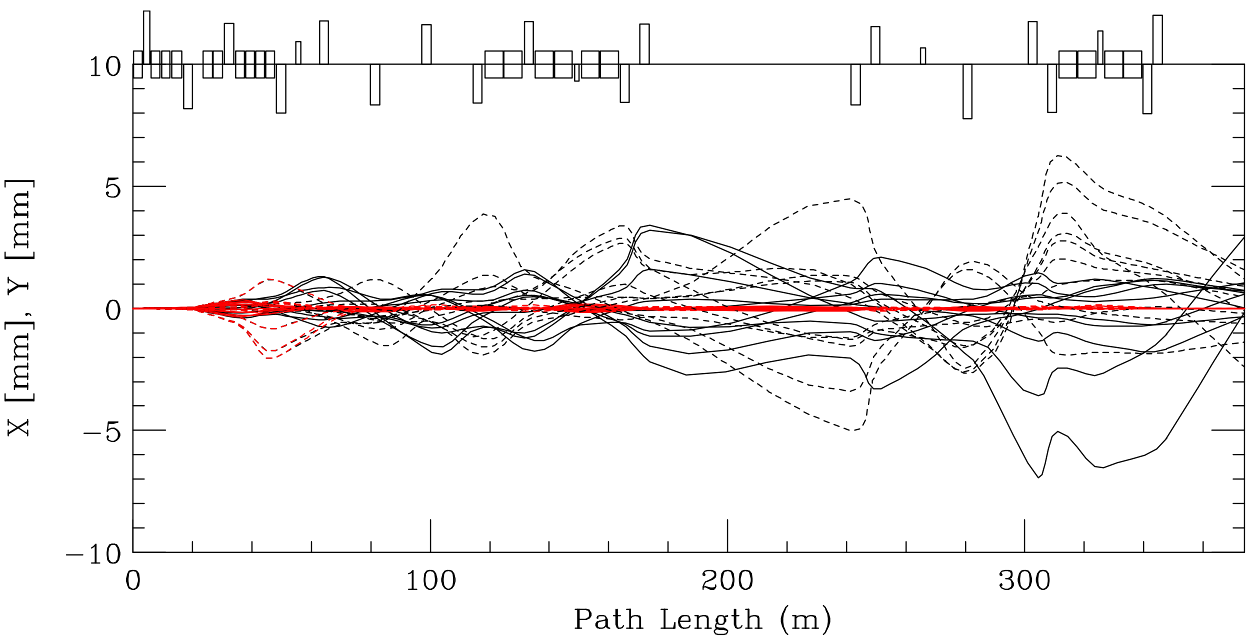

Figure 6. Uncorrected & corrected trajectories resulting from random magnet misalignments and dipole field errors

- After correction, $\Delta x = \Delta y = 0$ & $\Delta x' = \Delta y' = 0$ at the target, and beamline offsets are reduced to:

$\Delta x(rms) = 0.07$ mm $\Delta y(rms) = 0.25$ mm

$\Delta x(max) = 0.33$ mm $\Delta y(max) = 2.02$ mm

- At 120 GeV/c MI correctors are capable of 150 μr horizontally & 75 μr vertically. The strengths required for the simulated orbit corrections are:

$\theta_X(rms) = 16.14$ μr $\theta_y(rms) = 21.10$ μr

$\theta_X(max) = 52.90$ μr $\theta_y(max) = 68.47$ μr

SUMMARY

- The NuMI beamline is a modular design, with 2 matching sections, periodic FODO cells, & a special straight section insert across the carrier pipe.
- The lattice is constructed from 21 quadrupoles — a reasonable number for a beamline of this length.
- $\beta < 60$ m throughout the MI-end & FODO sections, and $\beta < 120$ m everywhere else.
- Lattice functions are not overly sensitive to error sources — arising either from optical mis-matchs or gradient errors — and are correctable through the matching sections.
- 21 BPM's & 19 MI-style dipole correctors provide for excellent orbit control.